A Complexity Theory Approach to Evolvable Production Systems

Regina Frei[1], José Barata[1]
and Giovanna Di Marzo Serugendo[2]

[1] New University of Lisbon, Quinta da Torre, 2829-516 Caparica, Portugal

[2] Birkbeck (University of London), Malet Street, London WC1E 7HX, United Kingdom

Abstract. Evolvable Production Systems differ from Reconfigurable and Holonic Manufacturing Systems by implying ontology-based process-specific modularity at fine granularity with local intelligence and a distributed control solution based on the Multi-Agent paradigm. Understanding the dynamics of such complex production systems is not feasible with traditional engineering. For creating the manufacturing systems of the future, engineers need to dare a leap in their ways of thinking. Complexity Theory and Artificial Intelligence can be a valuable source of inspiration for manufacturing engineers. This article illustrates how ideas from these scientific areas fit the problems and open questions of manufacturing. Some concepts, as Self-Organization and Emergence, need adaptation to be applicable in production systems; others simply require the right perspective. Finally, a vision of future EPS is outlined.

1 Introduction

Evolvable Production Systems, short EPS [1, 2], are a concrete solution to the requirements from the market such as stated within the Agile, Reconfigurable and Distributed approaches: they include high responsiveness, low down-times, ability to handle small series with many variants, and on-the-fly changeability. Together with ontology-based process-specific modules at fine granularity, a distributed control system using the Multi-Agent paradigm permits to quickly and cost-effectively adapt to ever-changing production requirements. The inspiration from Artificial Intelligence, Mobile Robots, Complexity Theory and Biology as well as other emerging sciences, as detailed in this article, will help EPS to cope with the turbulent environment, many-to-many multi-directional relationships and incomplete data and knowledge.

EPS have similarities with the Bionic, Fractal and Holonic approaches [3, 4], but besides considering system morphology, EPS strongly link product, process and system (see Fig. 1) by the means of detailed ontologies. As EPS, Emergent Synthesis, a Biological Manufacturing Systems approach [5], also focuses on self-organization,

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however lacks mechanisms usable for practical implementation and the product-process background.

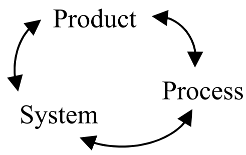

Fig. 1. Strong relations.

The purpose of this article is to show that Complexity Theory, Artificial Intelligence and related domains can be a valuable source of inspiration for manufacturing engineers, and to illustrate in which way many ideas found in these scientific areas fit the problems and open questions of the manufacturing world. Section 2 briefly explains the concept of evolvability in manufacturing as well as the distributed control approach required for Evolvable Production Systems (EPS). Section 3 illustrates the main sources of inspiration for new way of thinking, and some suitable concepts found in Complexity Theory and Artificial Intelligence are detailed. Among others, Emergence and Self-Organization are fundamental for EPS. Section 4 explains in which way they could be understood, and what their implications for production systems are. With their help, systems with far more advanced capabilities can be imagined, as outlined in section 5: the vision of future production systems. A brief summary follows in the conclusion.

2 Evolvable Production Systems

Evolvable Production Systems take complex systems in nature a metaphor for their own need to continuously adapt to an ever-changing environment. In this sense and in the context of manufacturing, Evolvability means the ability of complex systems to co-evolve with the continuously changing requirements, to undergo changes of different significance, from small adaptations on-the-fly to more important transformations. Ontology-based modularity at a fine granularity level, the modules' plugability as well as a powerful control approach based on the multi-agent paradigm are fundamental.

Evolvability is an enabler for tomorrow's production systems. Using a concept similar to LEGO together with local intelligence, they allow the user to build any required system and to modify it at wish. Through their module re-usability and life-cycle support, EPS considerably lower the system cost and enable the automation even in case of low production volumes and small lot sizes with frequent changes. Thanks to standardized, open interfaces, systems can gradually evolve through the addition, removal or exchange of modules.

The EPS control approach, avoiding re-programming, is crucial to ensure the modules' rapid plugability. Distributed approaches have the important advantage of low complexity in the individual control parts. They are modular and, by their nature, show emergent robustness when facing disturbances, component failure or other critical situations. Agent technology ideally matches distributed systems [6]. CoBASA [7] is an example of a Multi-Agent Shop-Floor Control System which focuses on rapid system reconfiguration. Equipment resources are represented by agents and form coalitions according to the current production requirements, given by order agents. In the operation phase, product agents ask to be treated in the way specified by their process plan. Agents exhibit both reactive and proactive attitudes and are referred to as "intelligent" and having "social behavior" based on a corresponding ontology.

3 Sources of Inspiration and Relevant Concepts

Numerous scientific domains have emerged in the last few years, investigating phenomena which EPS also exhibit. They can provide helpful tools and valuable theoretical background to cope with the complexity of manufacturing systems (see Fig. 2).

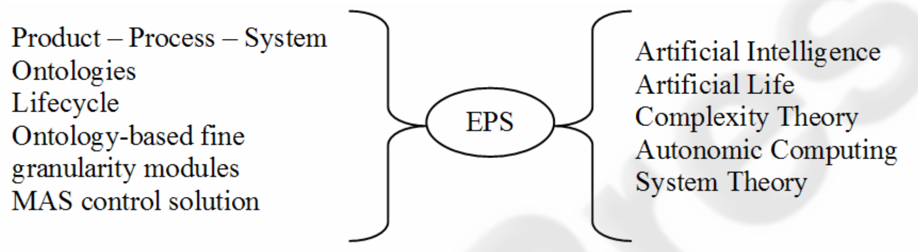

Fig. 2. Fundamental concepts and sources of inspiration for EPS.

3.1 Sources of Inspiration

In **Artificial Intelligence** the goal is often to create autonomous, intelligent behavior, learning capabilities, and adaptation mechanisms in machines used for sophisticated tasks. Typical examples are expert systems, which, in the case of EPS, provide support for human decision making. Machine learning can be helpful for improving equipment calibration procedures or for the automatic creation of complex skills based on simple skills in coalitions of equipment modules.

Complexity Theory looks for simple causes leading to complex behaviors [8]. Complex systems are spatially and/or temporally extended non-linear systems with many strongly-coupled degrees of freedom and high non-linearity. They are composed of numerous often simple elements and characterized by collective properties. EPS consist of equipment modules which are connected to each other and have multilateral interactions. Together, the modules form a system with the desired global behavior.

Chaos Theory studies cases where future outcomes are arbitrarily sensitive to tiny changes in present conditions [9]. The mathematical methods founded by Poincaré and Lorentz try to find patterns in this seemingly chaotic situations. Manufacturing systems often exhibit sensitivity to specific conditions and to disturbances. Certain factors lead to system breakdown while others have no significant effect. It is difficult to predict the critical circumstances and to cope with them.

A promising engineering approach based on Complexity Theory is described in "Foundations of Complex System Theories" [10]: the Synthetic Microanalysis. Combining the bottom-up and top-down views, it proposes an iterative journey from the whole to its parts and back.

System Theory and Cybernetics. All systems, however complex they are, have some kind of organization [11]. This structures or concepts, studied in System Theory, are often independent from the specific system or domain. In this sense, their understanding can help solving problems in a somehow generic way: the approaches can be applied to other cases – above all complex, adaptive and self-regulating systems. Cybernetics particularly treats the aspects of communication and control by focusing on circular feedback mechanisms in complex systems [11]. EPS need a dynamically modifiable organization. Their structure as well as constituents' interactions is fundamental for the good functioning of the systems. The trade-off between system autonomy and human control is a challenge for engineers.

Artificial Life including Swarm Theory and Mobile Robots. Scientists attempt to create life-like behaviors with the capability of evolution on computers and other "artificial" media. EPS are very similar to artificial living systems. They have a modifiable structure, will exhibit some kind of self-organization, can adapt to their environment, and react to stimuli. They are capable of evolving according to the circumstances, namely in terms of equipment states, and can incorporate newly available technology. As any living organism, they will include efforts to keep themselves in a constant well-functioning state through self-surveillance and self-management.

The concepts of swarm-building living organisms, such as stigmergy and coordination mechanisms found in schools of fish and bird flocks can for instance be used by mobile robots for the coordination with their fellows. The robots' autonomy and their capacity of collaboration are fundamental. Being reactive and proactive devices, they often include reasoning capabilities.

Agentified modules in EPS can be seen like the members of a swarm: their coordination can be based on similar strategies. Even if their mechanical properties are diverse, from a software point of view, they have similar or identical characteristics. They can participate in a coalition or withdraw from it, without disturbing the rest of the group, and thus permit true and immediate Plug&Produce functionality.

Autonomic Computing [12]. Although at another level than the other areas described above, Autonomic Computing provides a fundamental source of inspiration for EPS. Large computer-based systems, forming large networks and having complex and multiple interactions, become increasingly difficult to manage. As a consequence, software will be designed to itself undertake most management tasks, such as self-configuration, self-healing, self-protection and self-optimization. User interaction will be minimized and reprogramming avoided. Valid for computers, the concept of autonomic systems applies also to manufacturing systems in general and EPS in particular. Complexity must be hidden from the user. Systems need easy-to-use human machine interfaces.

3.2 Relevant Concepts

Out of these numerous fields of scientific studies, a set of the most relevant concepts is identified. Many of them are included in several domains and therefore no specific origin is indicated here.

Depending on the context, an **Agent** can be a human person, an association, an animal, or a piece of software, possibly connected to some hardware. The fundamental characteristics are identity, intelligence and the ability to act and react in order to persecute goals. Agents have at least a certain degree of autonomy and can compete or collaborate with others. The realization of Multi-Agent Systems can adopt various software technologies: early attempts used object-oriented or component-based languages and evolved towards programming languages and platforms directly supporting the concepts of agents [6]. Also web-services are an option, as used by Schneider Electric in their Service-Oriented Architecture [13]. When extended by a proactive part, web-services are de facto very close to agents. There are numerous successful experiences with agent-based systems in industry [14-17]. Rockwell Automation even develops agent-based systems where the agents run inside the PLC itself [18] instead of on separate computers. In EPS, Agents naturally represent the basic building blocks embedded into the different components of the production system.

Self-* capabilities as defined by AgentLink III [19] can concern installation, management, healing, configuration and other activities. EPS modules with self-* capabilities allow to minimize user interaction, i.e. to increase system autonomy. Self-Organization is of particular relevance: it is abundant in nature and a promising feature for artificial systems. A distributed diagnosis system for EPS, based on device Self-Diagnosis, is currently being developed at UNINOVA, Portugal.

Emergence. Complex systems most often consist of at least two different levels: the macro-level, considering the system as a whole, and the micro-level, considering the system from the point of view of the local components. Local components behave according to local rules and based on preferably local knowledge; a representation of the entire system or knowledge about the global system functionality is neither provided by a central authority nor reachable for the components themselves. They communicate, interact with each other and exchange information with the environment. From the interaction in this local world emerge global phenomena, which are more than a straight-forward composition of the local components' behaviors and capabilities. Typically, there is a two-way interdependence: not only is the global behavior dependent on the local parts, but their behavior is also influenced by the system as a whole. Emergent phenomena are scalable, robust, and fault-tolerant, i.e. insensitive to small perturbations and local errors as well as component failure, thanks to redundancy. They exhibit graceful degradation, meaning that there is no total break-down because of minor local errors.

Fitness functions and landscapes. In nature, organisms must be fit for survival and in this sense react to the requirements of the ever-changing environment. The closer an organism matches the fitness function, the better adapted it is to the current life condition. The criteria for endurance or elimination of new characteristics are most often multiple and form a "fitness landscape". In the scope of EPS, process requirements are the system's fitness functions / landscapes. Certain specifications are absolute: the marks must be absolutely reached – otherwise the process is not fulfilled. Others may indicate a direction, which the system can try to converge to (e.g. save energy, minimize cycle time, etc.).

Edge of Chaos, Far-from-equilibrium, Self-organized criticality. Constantly stable equilibrium states would block evolution. Dynamic systems get again and again into states where a little stimulus can trigger a major reaction. This gives the systems energy to evolve and makes new phenomena emerge. Illustrative explanations can be found in the books Tipping Point [20] and Critical Mass [21].

Complex Adaptive Systems (CAS) are systems that emerge over time into a coherent form, and adapt and organize themselves without any singular entity deliberately managing or controlling it [22]. Supply Networks have been recognized as CAS [23], and also EPS share many characteristics of them. They are many-body systems, composed of numerous elements of varying sophistication, which interact in a multi-directional way to give rise to the systems global behavior. The system is embedded in a changing environment, with which it exchanges energy and information. Variables mostly change at the same time with others and in non-linear manner, which is the reason why it is so difficult to characterize the system's dynamical behavior.

4 Self-Organization and Emergence in EPS

In areas such as biology and artificial life, emergence and self-organization have been discussed for many years and accordingly, definitions exist. Also for Multi-Agent Systems, these topics have been investigated [24, 25]. Their interpretation in scope of EPS is detailed here.

4.1 Self-Organization in EPS

Reasons for implementing self-organization in EPS are to minimize and facilitate user interaction, i.e. to hide complexity and increase system autonomy. Building and configuring a system composed of numerous entities with multi-lateral interactions is a highly complex task; the more autonomy the system has, the easier it gets for the user. Production systems tend to have many components of diverse nature which interact in many coupled ways. Agents need the capacity of (re-)organizing their collaboration themselves, in different forms and compositions, according to the needs, without passing through a central coordination point.

Self-organization is robust and adaptive with regard to its environment. In presence of perturbations and change, the system is capable of changing its organization while still maintaining its functionality. This means in practice that the control system should be capable of handling problems and if necessary finding alternative production ways. A major challenge in manufacturing applications is to let the system self-organize and at the same time, determine its behavior. Different from natural self-organized systems, artificial systems respectively EPS may require a kind of leader, a broker or (eventually human) decision maker. The control influence of this authority may be punctual in time and scope, e.g. at important strategic points.

4.2 Emergence in EPS

To bring the classical notions of emergence, discussed before, closer to the reality of engineered systems, two classes of emergence are proposed: For "full / complex emergence", the global level must show further development. There is non-linear dependence of the global functionality on the components and their interactions between themselves and the environment. "Basic / primitive emergence" means that the local-to-global dependence may be "quasi-linear" – but still, the appearance of the global phenomenon is not self-evident and needs some kind of "inspiration". An example is the classical Pick & Place mechanism: there are many different ways of putting together a gripper with translation / rotation axes – but not all of them lead to the desired functionality.

Not all equipment units are of the same granularity: an entire robot may as well be defined as a module, as a single actuator or a gripper, a gripper finger may be. Sensors and other fine granularity devices can play an important role in the emergence of complex skills: augmented with the right sensors, an axis does not only move, it can then detect the presence of other objects, determine distances or execute its own movement as a function of the state of others.

Some of the emergent phenomena will be favorable to the accomplishment of the system's task and have considerable potential for advanced system behaviors, such as the emergence of complex capabilities out of simple ones. These favorable emergent phenomena could and should be exploited. Others may be less adapted, disturbing or even harmful: e.g. system integration is supposed to function without unexpected symptoms. In nature, unsuccessful properties will be eliminated by the survival-of-the-fittest selection. Obviously, such a mechanism is not viable in manufacturing environment: harmful behavior cannot be allowed at any moment. How to cope with this problem in the case of EPS? Simulation can be helpful. Safety measures have to be taken in order to avoid problematic and dangerous situations.

5 Vision of Future EPS

Computing is becoming ubiquitous; little computing power devices will be present in every device. Manufacturing systems can then become powerful, easy-to-use and gradually more autonomous. EPS of the future might autonomously cover a large range of procedures, far more than today's production systems can. They will receive specifications of what to do, but not how to achieve it and which resources to use. This could lead to the following scenario:

To release an order into the system, *product agents* will be accordingly configured. They will carry their assembly plan and ask to be treated by *operation agents*. The kind of actions to be executed on the product parts, including specifications on precision, cycle time and other special needs, will be identified. This means that the exact *process requirements* will be determined, e.g. the way of picking a part, the geometrical trajectory to be made, the way of bringing parts from a feeder to its place of insertion, etc. The system must be capable to find and organize the right resources for each function, to grant for their successful execution as well as sustainable system management, as will be detailed below.

The *use of the equipment resources* is yet to be chosen: this happens by exploring the existing system with the help of a dynamically updated map of the shop floor respectively the present modules as well as the modules available in the storage department or eventually in vendors' module pools. In collaboration between operation agents and *resource agents*, several possibilities of executing the required processes will be determined and the best will be chosen. The criteria for this selection can be a standard set or specified by the user. Finally, the user will be informed about possible necessary addition, displacement or removal of modules. The required resources will be autonomously configured / calibrated for the processes, and the needed resource coalitions will be formed to create the complex skills. No re-programming is needed. Agents work autonomously and collaborate with other agents. Modules register in a resource so-called cluster and, from this platform, to dynamically form coalitions with other resource agents according to the incoming production requirements.

The entire *real time execution* is then taken over by the system, which functions with a high degree of autonomy, too. Modules at fine granularity, incorporating reactive and proactive intelligence, will exhibit *self-* capabilities*. Systems are able to do self-surveillance and self-maintenance, i.e. to observe their internal state and if necessary take corresponding measures, to schedule regular maintenance, to announce the eventual need for staff interaction before problems become acute. Autonomic systems self-optimize, meaning that they continuously search for ways to optimize their operation. They can self-diagnose and self-heal in order to predict and avoid respectively solve most problems autonomously and, in case of the need for user interaction, make it as easy as possible by indicating the defective part, the problematic part interaction and proposing corresponding corrective measures to the shop floor staff.

Of course, such a fundamental change in the way systems are built and especially run cannot be achieved from day to the next; the approach has to advance *step by step*. E.g. concerning decision making, the systems can neither be expected to become fully autonomous at once nor can users trust them immediately. Gradually increasing independence is more sustainable. At first, the system automatically collects information in order to support human decision making. In a next phase, it gives advice and proposes solutions, taking note of user preferences. Later, the system indicates the best-fitting solution as well as alternatives and requests user confirmation. And finally, after these learning phases, the system takes decisions alone.

In this sense and as a conclusion, systems might evolve in a way that they develop capabilities which the system designers have never thought of: systems could eventually offer services which they have not originally been built for.

6 Conclusion

In order to cope with today's and tomorrow's manufacturing needs, new solutions are required. *Evolvability* is a key to success: the capability of systems to evolve together with the production requirements as well as the strong product-process-system link are crucial. EPS provide ontology-based process-specific modularity at a fine granularity and a distributed control approach using the *Multi-Agent paradigm*. *Self-Organization* and *Emergence* allow system autonomy, which can considerably facilitate system installation and operation by hiding complexity.

EPS share many aspects of Complex Adaptive Systems and therefore need to be addressed as such. Traditional engineering cannot offer corresponding tools. Complexity Theory and other emerging scientific domains have the potential of providing valuable help to cope with CAS and the engineering of such systems, offering the possibility of implementing advanced system capabilities.

The ideas described in this article require a stepwise approach. Some of them still need theoretical elaboration, while others are already fully or partially implemented on a prototype at UNINOVA, Portugal. The NOVAFLEX assembly system has been agentified: each module is an agent, and the multi-agent control system is operational. The lab installations are built of legacy components from diverse suppliers and include two industrial robots, different grippers, a warehouse and conveyor circuits. A distributed diagnosis system, based on a Service-Oriented Architecture and using device Self-Diagnose, is currently being developed. In parallel, tiny computing devices for supporting MAS are being elaborated. Integrated in any kind of equipment unit, they will make computing capacities ubiquitous, also in the manufacturing world.

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